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Mylonite, ductile shear zone and serpentinite diapir: Detachment faulting and later thrusting around the Moho horizon, Northern Oman Ophiolite

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Abstract

Three different types of shear zones were found around the Moho horizon in the Bat area, west of Sohar, northern Oman Ophiolite, including a mylonite zone, ductile shear zone, and brittle serpentinite fault. The area is occupied by peridotite in the west and gabbro in the east, forming a dome structure. The mylonite of ultramafic and gabbroic rocks including isoclinal micro-folds and composite planar fabrics are developed as the first stage of deformation. The ductile shear zone, of the second stage, overlies the mylonite and is characterized by a steep foliation with complicated folding both sinistral and dextral. On the other hand the third stage brittle fault is interpreted to be originated from first serpentinite diapir, then to be involved later in the east-verging thrust fault zones. Those three stages may be part of a series of deformation within the context of normal fault detachment deformation in the mid-oceanic ridge realm. The first normal sense may be composed of the mylonite-bearing detachment fault in the depths, then ductile shearing in the middle depths, and serpentine diapir in the shallow depths during the oceanic plate stretching, but the east-verging thrust in the last deformation in the serpentinite fault may be attributable to the back thrusting of the horizontal compressional stage, maybe of the obduction process.

Keywords: Oman ophiolite, Moho, ductile shear, mylonite, serpentinite diapir, back thrust.

Introduction

Recently, detachment faulting under the sea has been known from the spreading ridge areas, in some places associated with a mega mullion structure (Tucholke *et al.*, 1998; Dick *et al.*, 2003, Ohara and Okino, 2001 and others), and somewhere such faulting produced mylonitic rocks. Those detachment faults are thought to be characteristic in the ridges with slow spreading rate.

However, the details of detachment faulting have not yet been reported from any ophiolites on land. I found similar geologic features around the Moho horizon (crust-mantle boundary) in the northern Oman ophiolite from the Bat area of Wadi Zabin, west of Sohar (Fig. 1), although the Oman ophiolite is thought to be a product of fast spreading ridge, soon after spreading to be obducted to the west (El-shazly and Coleman, 1990), but the geological processes what kinds of deformation occur during such tectonics have not yet been fully described nor discussed.

This paper focuses on the extensive flow and shear structures including a mylonite zone, a ductile shear zone and an additional brittle fault zone in this area. In this paper, these shear zones were structurally analyzed to present a stage model with considerable change of deformation conditions and different sense of shears in the deep to shallow levels.

These shear zones may be interpreted to imply three different time dependent stages, but some may be involved in a single large series of detachment zone development and associated deformation around the spreading ridge. Some later modification around the continental margin could also be adoptable. The detachment faulting might be due to the local features for the edge of the segment, where forcible spreading occurs.

Geologic setting

The Bat area is situated in the upstream of Wadi Zabin in the Fizh block, 60 km to the west of Sohar, where the ophiolite sequence covering from upper mantle to oceanic crust is exposed preserving the original structure and stratigraphy (Fig. 1). The general attitude of the ophiolitic rocks in the Fizh block is NNW-SSE strike with gentle eastward dip (Boudier *et al.*, 1996).

At the Bat area, however, a gentle dome structure is developed as traced by schistose, mylonitic ultramafic and gabbroic rocks of tens of meters thick (Figs. 2, 3). The gabbroic mylonite zone is further dislocated by a strong ductile shear of NW-SE direction, being different in fashion and strike than the mylonite (Fig. 4). To the east there is a distinct fault with N-S to

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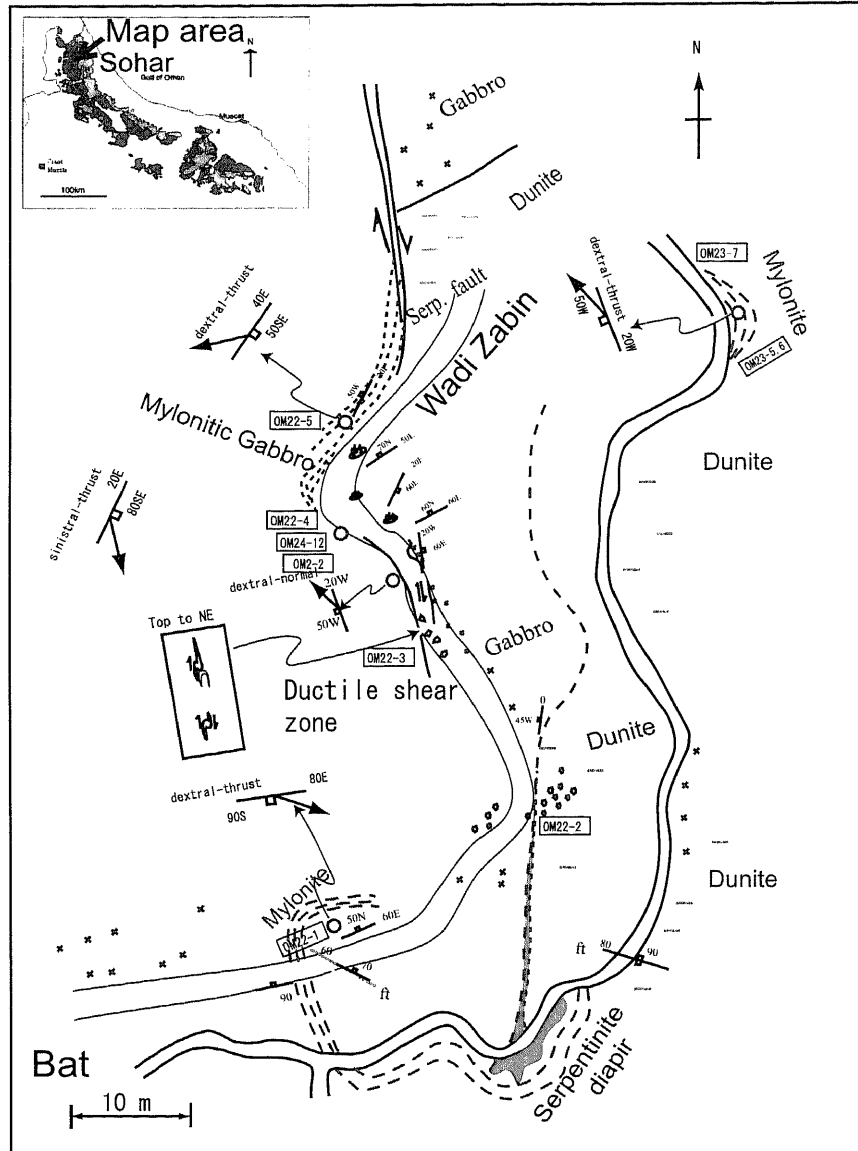


Fig. 1 Outcrop map of the Bat area, showing the principle lithological units, features and sense of shears.

NNW-SSE strike and gentle westward dip. The fault zone is composed entirely of sheared serpentinite of several meters width. As a result there developed three different kinds of sheared rocks; mylonite in a dome structure, a ductile shear zone with steep dip, and E-verging brittle serpentinite fault (Figs. 2, 5).

Method

The method used for this study was carried out as follows; field work was performed on the structurally lowermost layered gabbro at the transition zone between the mantle harzburgite and cumulates where ductile shear zones are concentrated. Fifty-eight samples with precise measurement of orientation were

collected from mantle and crustal sections for detailed microscopic study. The representative samples were studied in thin sections for sense-of-shear markers, and by X-ray diffraction to show the bulk mineral components of each sample. Detail petrochemical studies have already been done by Obara *et al.* (1999), and the results for the temperature estimation for metamorphism were referred to. The microscopic observations are made for sections for XY surface (foliation plane), XZ surface (flow plane), and YZ surface. A mineral lineation is usually parallel to X.

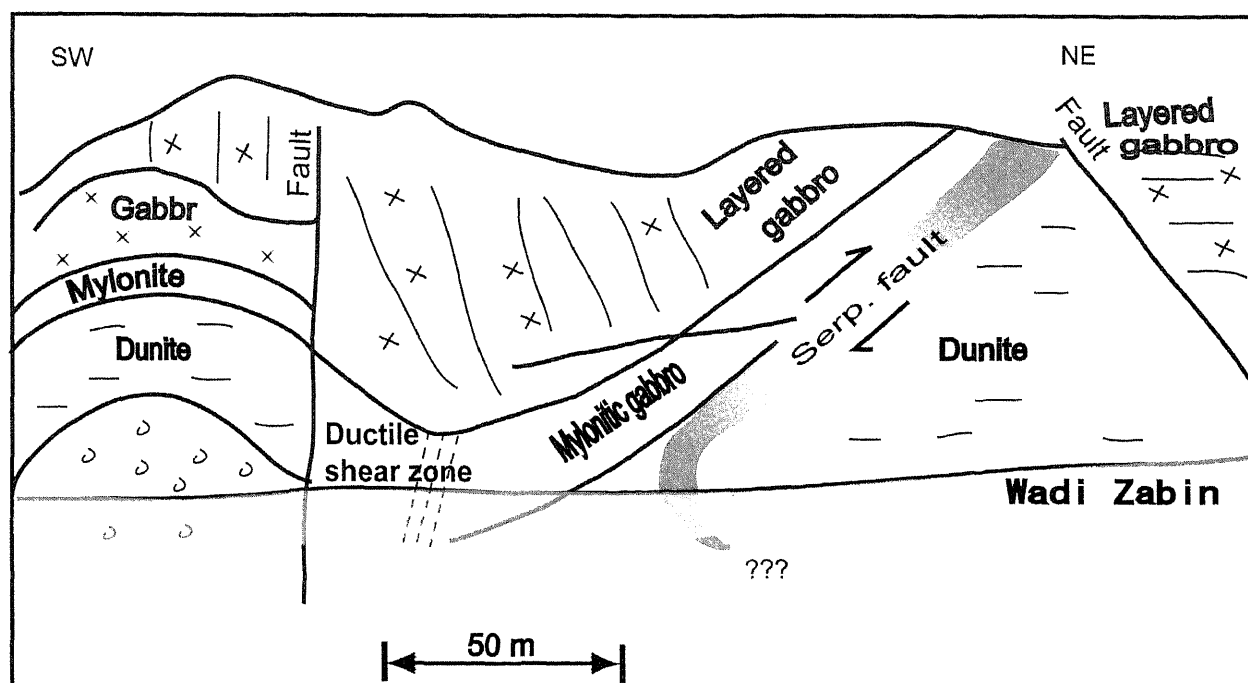


Fig. 2 Schematic profile of the study area, showing the distribution of mylonite, ductile shear zone and serpentinite fault as a serpentinite diapir.

Geologic structure of the Bat area

Mylonite dome structure

The mylonite body of ultramafic rocks are strongly foliated with intense isoclinal microfolds characterized by the coexistence of the porphyroclasts parallel to the foliation (Fig. 3-a to h). Those rocks form a dome structure around the Bat village on 100 m scale. A meter-scale small diapiric structure with a gabbro block is seen in the center of the dome structure (Fig. 2).

Vertical ductile shear zone

Intensely sheared gabbroic zone of several meters wide on the east of the mylonite is characterized by the development of sheared mylonitic texture, but different fashion from the domal part, as porphyroblast-bearing blastomylonite overlying the early mylonitic texture (Fig. 4).

The shear zone trends approximately NW-SE and maintains relatively constant orientation with vertical dip concentrated within a meter-scale narrow zone. Many isoclinal folds of micro to meso-scale are developed in several centimeters to tens of centimeters width (Fig. 4). The shear zone bears many leucocratic lenses stretched parallel to the mylonite foliation. Folded geometric features showing mainly dextral sense-of-shear, but in some parts sinistral sense-of-shear (Fig. 4-b).

Serpentinite fault

Strongly scaly cleaved serpentinite (chrysotile and lizardite) body of several meters width with NNW strike and moderate westward dip is developed to the east of the ductile shear zone. The serpentinite body seems to form a fault zone, intruding into the mylonitic gabbro, and has complex folds within the body of a dominant thrust sense with some subordinate normal sense (Fig. 5). The serpentinite is marked mostly by low temperature deformation with brittle fashion. Important is that the general vergency of this serpentinite fault is east direction of dominant thrust sense, in the contrast with the common west vergency in the whole Oman ophiolite.

Stage of deformation

As mentioned above, there are three different styles of shear zones or faults in the small area at the Bat area. Among the three, the second stage ductile shear zone overlaps the mylonitic texture of the first stage to be defined by cataclastic and ductile shearing. The ductile shear zone dips with high angles, whereas the mylonite forms a dome structure. The ductile shear zone merges and is dislocated by the third stage serpentinite fault zone, which is far brittle than the ductile shear zone, so that it must be much shallower product.

In this chapter, I consider that the mylonite is of

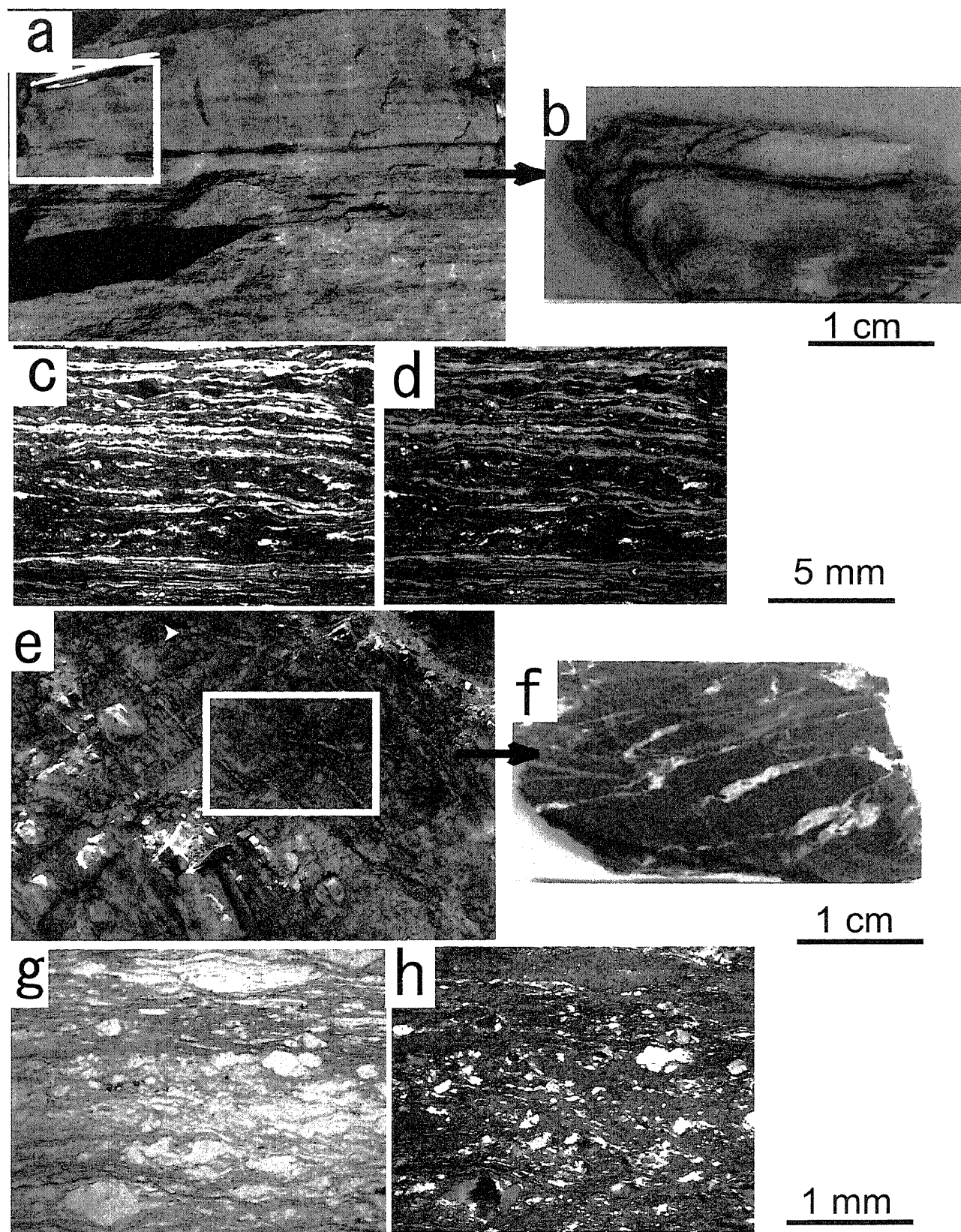


Fig. 3 Sheared layered mylonite body, showing oblique foliation and S-C cleavage bands. a, b: Outcrop and sample photos of sample Om 22-2/1. c, d: Photomicrographs of thin section of Om 22-2/1, open and crossed nicols. e, f: Outcrops photos and sample of Om 23-2/6. g, h: Photomicrographs of thin section of Om 23-2/6, open and crossed nicols.

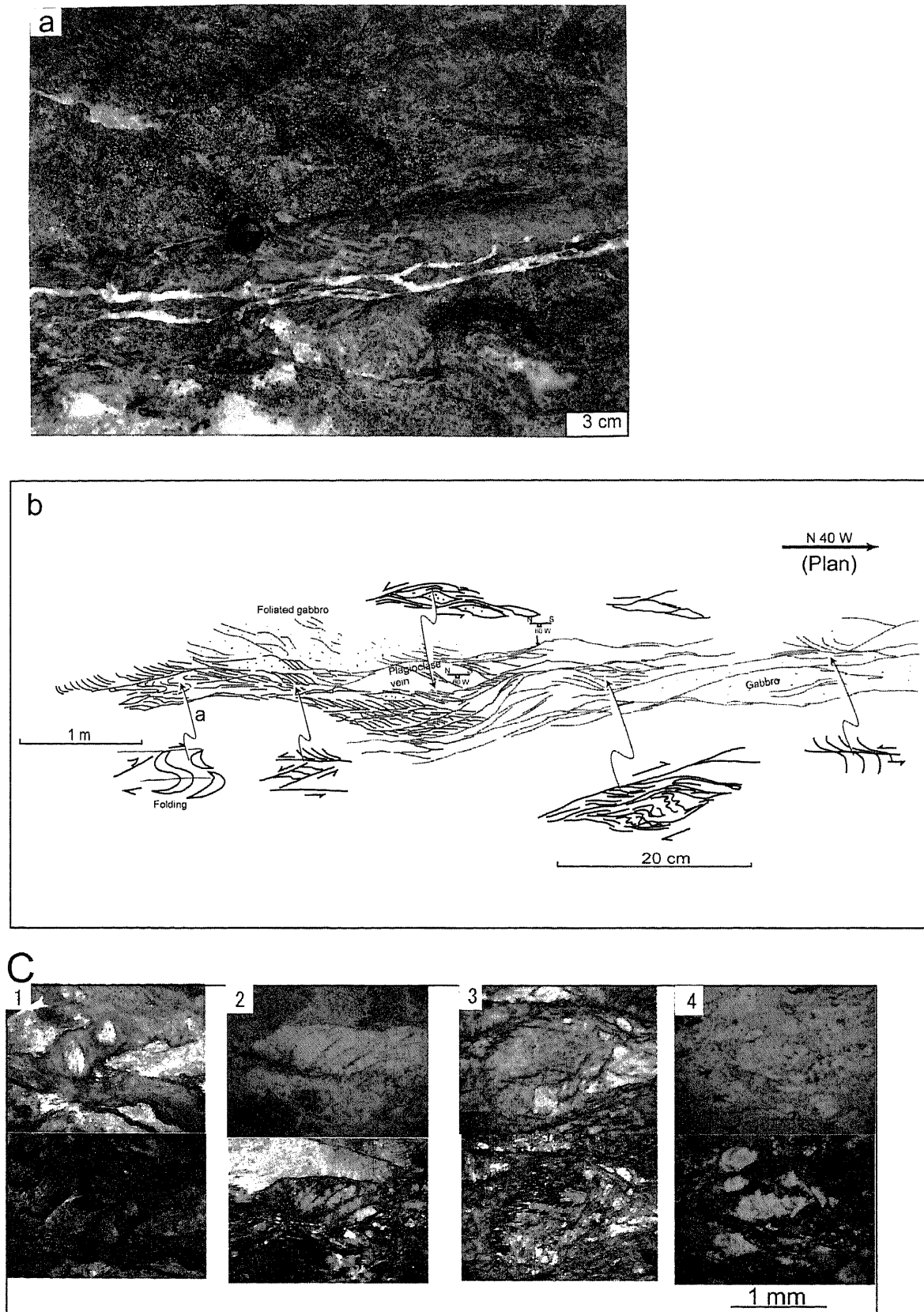


Fig. 4 Features of the ductile shear zone and outcrop photos and sketch (a, b), and photomicrographs of thin sections (open upper, crossed nicols lower) (c). c-1: sample Om 22-2/3, c-2: Om 22-2/5, c-3: sample Om 24-2/12, c-4: sample Om 24-3/2.

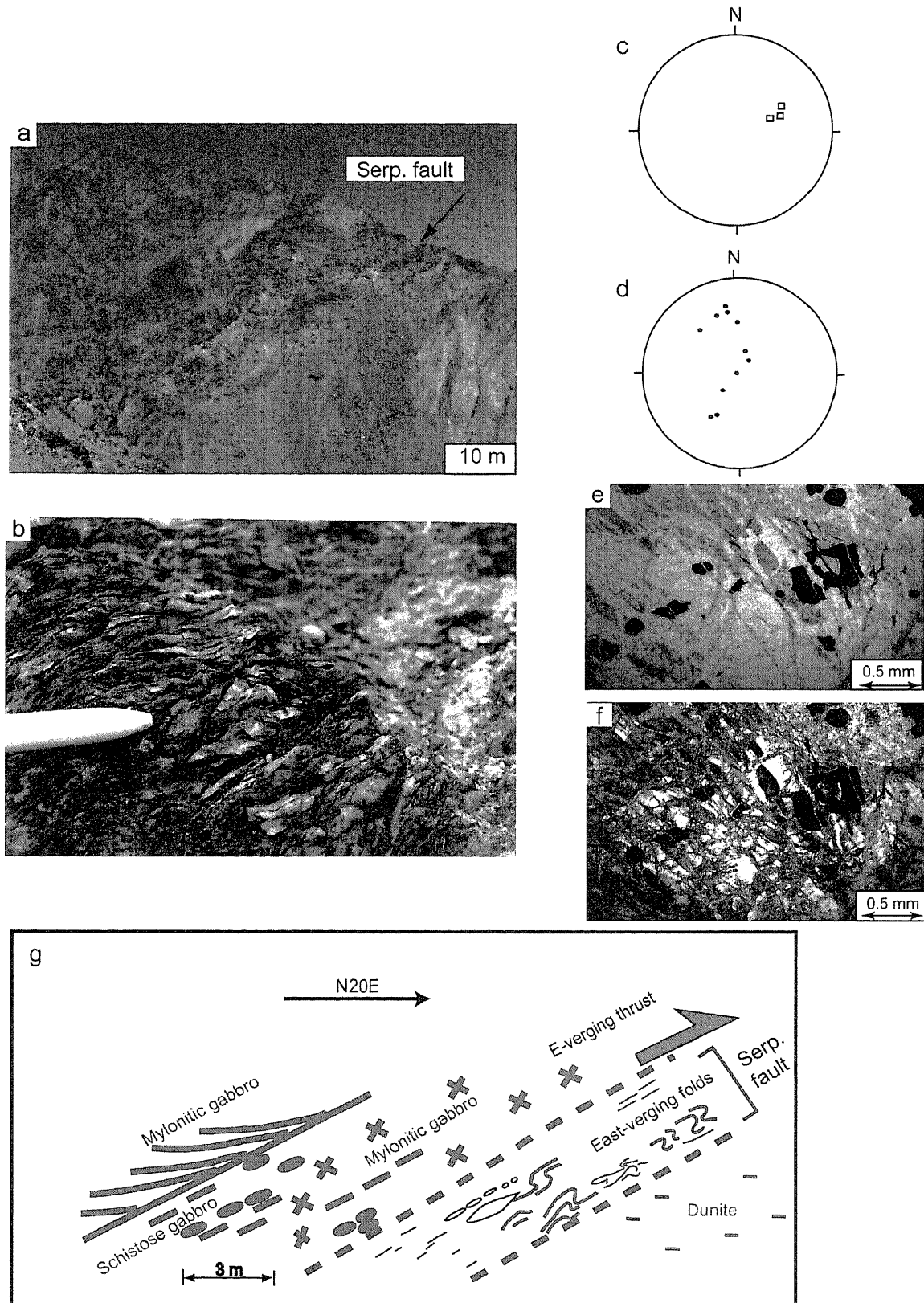


Fig. 5 "Serpentine fault" as a serpentinite diaper interpreted as a back-thrust. a: Outcrop photo looking the west. b: Outcrop photo. Pen indicates the north. c, d: Stereographic projection of fold axis in serpentinite (c), of axial surface (d). e, f: Photomicrograph of thin section (open (e) and crossed nicols (f)). G: Schematic sketch of the outcrop, showing structural elements.

the first stage of deformation, followed by the ductile shear as the second stage, and finally the deformation of serpentinite fault is developed, although these three may be connected as one single series of deformation as discussed in the final chapter.

Microscopic observations

There are a large number of useful criteria for the deduction of the sense-of-shear in mylonites or sheared rocks on a microscopic scale, such as stair stepping of the wings, pressure shadows, shear band cleavage, and a composite foliation as (S-C-C'). The C or C' foliation indicates the later stage than S. Examination of the microstructure of mylonitic rocks in thin section shows different categories of shearing modes representing different stages of deformation and recrystallization. According to Obara *et al.* (1999), most deformations occur at relatively high temperature, 500–700°C in the Bat area. The texture and grain size of the rocks can be related to the conditions of temperature and pressure. Because the sense of primary foliation (S) is not known, the secondary foliation, C or C', sense is dominantly described.

Stage 1: Mylonitization

Mylonite is of the first stage of deformation, according to the cutting relation to other types of rocks. In one mylonite sample (Om 22 1/2) (Fig. 3-a, b), chlorite dominant flow texture shows dragged, strongly sheared porphyroclasts, stretched at their edges to form symmetrical wings by S foliation (Fig. 3-c, d). However, by means of the secondary foliation, the mylonite texture with dragged porphyroclasts forms compositional layering. Such attitude of the porphyroclasts is interpreted to be an E-W trending fault of dextral slip of top to the west with down oblique fault.

In another mylonite sample (Om 23-2/6) (Fig. 3-e, f), a chlorite dominant sample with porphyroclasts in fine-grained mylonitic part shows fibrous growth and strong preferred orientation. Stair stepping aggregates forming wings or tails are derived from secondary foliation, which generates asymmetrical porphyroclasts through stages of deformations and crushing. The S-C' shear band cleavage are distinguished (Fig. 3-g, h). Other microstructural features are isoclinally folded veins of epidote, undulose extinction of plagioclase crystals and dislocation. The sense-of-shear of the secondary foliation indicates a thrust component-bearing dextral-slip fault with N20° W strike and 50 ° W dip, meaning top to the east.

Stage 2: Ductile shear zone

Ductile shear zone has different attitude and different grain size than the mylonite (Fig. 4). In one sheared gabbro sample (Om 22-2/3) (Fig. 4-c-1), clinopyroxene and tremolite porphyroclasts are commonly rotated and deformed in very fine mylonitic matrix during the second stage shearing. Plagioclase gash with wavy extinction is developed. Such porphyroclasts indicate a normal fault-component having dextral strike-slip fault of strike N 20°W and dip 50°W. The composite S-C shear band cleavage is seen where displacement of the grains is noticeable.

In another sample (Om 22-2/5) (Fig. 4-c-2), mylonitized gabbro sample has fish-shaped porphyroclasts stretched asymmetrically with pressure shadow. The aggregates of matrix surrounding the porphyroclasts show transition from micro-breccia to mylonite, to be called protomylonite texture. It is interpreted that such porphyroclasts show gentle NE dipping oblique-thrust with dextral strike-slip component.

In another case of sheared gabbro sample (Om 24-2/12) (Fig. 4-c-3), stair-stepping or pressure shadow of the wings shows conjugate sets of S-C' type shear band cleavage. Coarse grains of plagioclase which are cataclastically crushed have crushed tremolite matrix (Fig. 4-3). This texture represents foliated protomylonite texture. The direction of movement with respect to shear sense indicators shows either oblique sinistral or dextral fault in different parts of the sample, probably as the different sense in the different wings of folds as the C' is due to the axial surface foliation of the folds.

In another sheared gabbro (sample Om 24-3/2) (Fig. 4-c-4), extremely compressed stair-stepping or pressure shadow of porphyroclasts occurs in S-C' shear bands cleavage. Serpentine-rich bands show kink bands. The sample has equigranular porphyroclasts, and the matrix shows protocataclastic texture. The porphyroclasts are mainly tremolite in the foliation, indicating thrust fault component-bearing dextral strike-slip fault of strike N 40° W and dip 40° W. Thus, stage 2 deformation has some brecciation of semi-brittle conditions, suggesting the less ductile than stage 1.

Stage 3: Serpentinite fault

This serpentinite fault is a new finding, and is thought to be a key to understanding the tectonics of the late stage of deformation. Within the serpentinite fault, various shapes of folds with east-dipping axis are developed (Fig. 5). At least for the brittle features of deformation, the final movement of this fault must

be under shallow conditions, and is thought to be the last stage. In one sample (Om 2-3/1) (Fig. 5-e, f), taken from a block within the discrete shear zone, brittle brecciation is shown.

Tectonic interpretation and discussion

Mylonitization

Strong ductile deformation under high temperature conditions forms the mylonite shear zones in parallel to the general layering of the ophiolite sequence. This zone separates the lower sequence of tectonites from the upper crustal sequence, and its thickness attains around 20 meters. Therefore the formation of mylonite shear zones must account for the existence of large scale detachment movement taking place parallel to the ridge at a low angle during spreading. These observations indicate the main shearing is due top to the SE.

The dominant dextral N-S to NNW-SSE shear zones are subparallel to the ridge spreading direction that could be related to strike-slip faulting, which represents primary zones of weakness under relatively high temperature. Determination of sense-of-shear suggests that the initial detachment motion could occur as top to the east in terms of the present day orientation parallel to the ridge axis

This interpretation is supported by the existence of two sets of shear zone systems of the early stages, firstly, shear zone of layer parallel fault in response to the original Moho, and secondly, local detachment zone where mylonite is produced. Thus the first stage is thought to be related to the main stage of sea-floor spreading.

Ductile shear deformation

Although the mylonitic ductile deformation took place in the peridotite and gabbro around the Moho at the lowermost crustal sequence, the local folded sheared gabbro zone of semi-brittle deformation process, medium to high angle dipping, was formed into the foliated layered gabbros unit after the main foliation formation. The ductile shear zone may be of shallower expression of deformation of the mylonitic structure, but the disposition of the zone is different, possibly by the later displacement of the fault zone, so that even though it is involved in the same series of the deformation, it might be of later stage. In the former case, it might be shallower part of the ridge production along the detachment fault in the gabbro horizon.

These macroscopic scale folds are considered as products of deformation process after the first stage mylonitization. The main structural divisions attributed

to the formation of the shear zone are either of dextral and sinistral types depending upon the different local parts of folds. In general it might be expected that with increasing strain the rocks encountered in a shear zone. Increasing strain may affect the structural elements of the shear zone, all of which have a distinctive geometrical relationship with the shear zone itself. Furthermore, such rocks may have been subjected to multiple periods of deformation, often under different conditions. The deformation mechanisms involved in the deformation of the rock are produced during compression process throughout the zone. This compression factor associated with mechanical deformation at different structural levels produced a composite mixture of sense-of-shear.

Another interpretation is that the ductile shear zone is of the far later stage than the detachment, after the conversion from spreading to subduction. In such a case, the result of intra-oceanic detachment at the spreading ridge occurs as overthrusting (obduction). In the latter case, the tectonic setting of emplacement is related to subduction zone and collision on the Oman ophiolite, because it is thought that the plate convergence occurred very close to the former Oman spreading ridge. The conversion of the plate which may have been initiated by the change of relative motion of Afro-Arabian plate from E-W to NE-SW introduced changes of deformation metamorphism, and magmatism. The continuation of the northward drift of the Afro-Arabian continent after collision led to the Oman ophiolite to ride over it (Yanai *et al.*, 1991).

This structural situation is interpreted to be resulting from the mechanism of ophiolite obduction with vertical rotation N 40°W. Several large scale shear zones cutting the mantle peridotite were proposed to trend the same direction.

When I refer to this ductile shear zone to the large scale shear zones of NW-trend of Yanai *et al.* (1991), it might be possible that one of them reaches this area. We need further mapping much wider area.

Serpentinite fault

From the drag and asymmetry of the folded serpentinite foliation, brittlely deformed as scaly cleavage with folding, it is dominantly eastward-verging thrusting. The basic scenario for the formation is continuing input of water in the mantle from the sinking slab or ridge area along normal faults. The serpentinite at this step exhibit a much shallower deformation than the former two stages. It coincides with the idea that it tectonically intruded at last by collision-derived force related to Afro-Arabian

continent collision as a back thrust.

Comparing with the other Moho of the Oman ophiolite

The Aswad massif just north of the Fizh block stands as one of the largest and the simplest internal structures among the 12 principle massifs composing the Oman ophiolite belt (Nicolas *et al.*, 1996). The structural mapping has revealed that the most intense deformation of the massifs such as major folds and shear zones around the Moho area were not related to the obduction but to the ridge propagating activity (Nicolas *et al.*, 1996). In the Aswad massif the only deformation was induced by shearing while the Aswad ridge was still active similar to other parts of the Oman ophiolite belt (Boudier *et al.*, 1996). The main part of the mantle unit in the Aswad massif is composed of high temperature harzburgite with minor dunite interlayered with pyroxenites. Low temperature peridotite is found in the Aswad massif restricted to N trending shear bands while it is absent at the Bat area. Shearing is dominantly west verging as in the other massifs of the belt. The lower gabbros show plastic deformation and norites occur along band rich in shear zones of amphibolite facies metamorphism. Compared to the gabbros at the Bat area, the magmatic foliation and internal structure in the lower gabbro unit where mylonite deformation at relatively high temperature conditions is ubiquitous.

Hydrothermal veins of dark green hornblende, epidote and prehnite are abundant in the gabbros of the Aswad massif and of the Bat area, while dykes are remarkably abundant in the Aswad massif. Mineral lineation and magmatic foliation are parallel to the plastic flow related lineation in the mantle peridotites in the lower part of the gabbro section. This behavior of magmatic foliation and lineation is also the same as in the Bat area. In these settings the mylonitic deformation around the Moho is common within the gabbroic rocks

The Bat area is characterized by strongly ductile shear zones trending NW-SE showing mainly dextral sense-of-shear, but in some parts a mixture of dextral and sinistral sense-of-shear coexists. General descriptions of the major shear indicators are sinistral in the Aswad massif trending to the N.

Observations of mantle diapir believed to represent a young ridge propagating into slightly older lithosphere (Boudier *et al.*, 1996) suggest that steep high T structures are seen in the mantle unit.

In the present model of the mylonitization and ductile shear zones around the Moho as already

mentioned on the basis of the shear senses are intense as confirmed by high T plastic deformation particularly within the Moho horizon that separates the mantle harzburgite from the overlying crust. The detachment related tectonics such as faults, mylonitization and shear zones are ascribed to the ridge spreading tectonics, suggesting the possible relationship between the Aswad and Fizh massifs ridge segments accentuated by present day fast spreading ridge system. Absence of graded bedding in the gabbros would imply slow spreading during the formation of the Aswad massif rocks (Nicolas *et al.*, 1996).

In the other areas of the onland ophiolite examples, the Bay of Islands one (New Foundland) is very close to our observation from the Bat area. The geologic similarities to the second stage was mapped in the Lewis Hills massif, Bay of Islands Ophiolite, where a localized listric detachment zone near the top of the lithospheric mantle as a high temperature ductile zone generated at an inside-corner setting (Suhr and Cawood, 2001).

On the other hand, serpentinite diapir has been reported from the ocean example of the North Atlantic. Serpentinite diapir may extend to the overlying crustal section through structural weaknesses and the final production of this process is the emergence of serpentinite on the seafloor (Reston *et al.*, 2001) (Fig. 6). The continuous penetration of water causes the formation of serpentinite diapirism at the seafloor. The situation of the detachment faults and associated serpentinite diapir to the ocean floor after water seepage to the mantle of Reston *et al.* (2001) is extremely similar, suggestive to consider that the whole deformation of our three stages is included within one single large series of development of detachment fault close to the spreading ridge.

Conclusions

Combination of structural characters, attitude and vergences in the Bat area indicate that flow and shear structures occur at three stages, first high temperature conditions to form ductile deformation, and later semi-brittle deformation at lower temperature. The mylonite section in the Wadi Zabin and Bat areas are deformed by ductile flow, in other words, the stress-supporting network is affected by dynamic recrystallization at relatively high temperature. It is concluded to occur as a detachment zone parallel to the Moho plane.

Major mylonite shear zones have been discovered in the peridotites and gabbros of the Oman ophiolite are oriented N-S, NNW-SSE trend with dextral dragged sense-of-shear. Mylonite zones observed under the

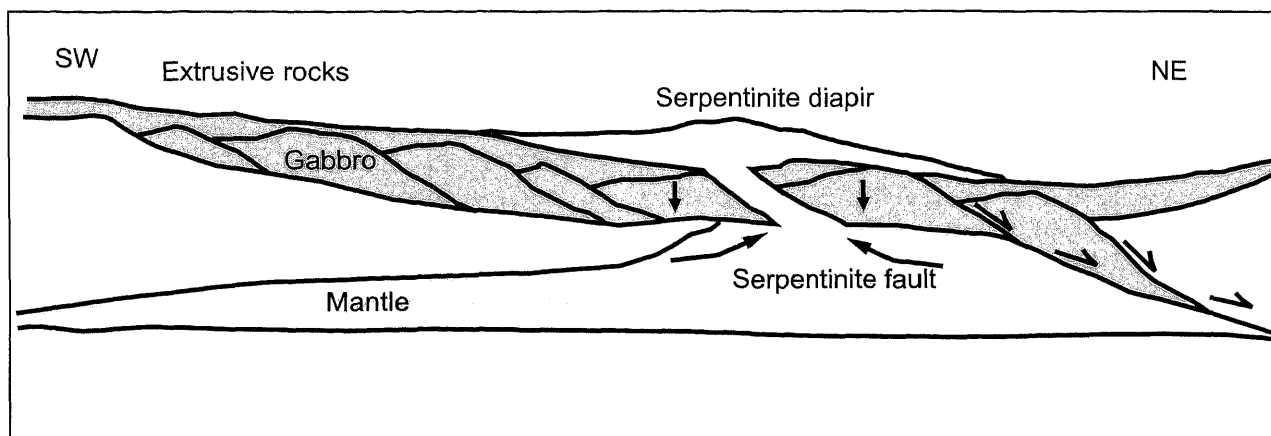


Fig. 6 Model for serpentinite diapir breaks through the mantle to form serpentinite body (after Reston et al., 2001).

microscope are marked by porphyroclastic to mylonitic microstructures and have clear composite structure called S-C-C' shear band cleavage, which is developed in strongly foliated mylonites. The metamorphic conditions of mylonite are recognized by recrystallized mineral assemblages of pale green tremolite, chlorite and serpentine. The result may commonly indicate that the metamorphic conditions occur associated with relatively high temperature metamorphism. The mechanism of obduction of this immense ophiolite body is appeared to be a two-step process affected by emplacement-related deformation.

First there is the oceanic detachment which formed the shear zones around the Moho. Secondly, the development of local highly deformed and folded mylonite sheared gabbroic zone occur with high angle within the foliated gabbro body trending vertically towards N 40°W. The shear zone is characterized by foliation of semi-brittle (plagioclase cataclasite) in medium to high angled shear zone with the appearance of porphyroclast minerals with a mixture of dextral and sinistral sense-of-shear. Contrasting with the ductile manner of deformation in the earlier part, the deformation of serpentinite at this step which is marked mostly by lower temperature deformation is observed. This serpentinite fault zone is strongly sheared with clear folding and spaced schistosity. This zone was formed due to the hydration process in the mantle. This hydration and deformation may have occurred together with the detachment faulting close to the spreading ridge area, or along the Oman ophiolite subduction zone. However, the east-verging thrusting might be attributable to the continental margin collision tectonics along with the obduction as the back-thrusting. Although previous interpretations of the driving mechanism introducing this serpentinite

block were proposed, we introduce here a collision model where a strong push component was proposed for the driving force of the serpentinite fault zone over the mantle peridotite and gabbroic bodies. The tectonic model for the collision related overthrusting of this collision zone is resulted in the collision of the Afro-Arabian continent. The fault zone is strongly suggested to be verging towards the east as a back thrust fault.

The detachment faults are thought to be characteristic in the slow spreading rate ridges. However, within the fast spreading ridges, the detachment might occur at the edge of the segment, where forcible spreading occurs.

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